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Groundwater conditions along the seawater/freshwater interface on a volcanic island and a depositional area in Japan

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Fresh groundwater comes in contact with seawater at the downstream end of its flow system. Most previous work has discussed the shape of the seawater/freshwater interface on the basis of Ghyben-Herzberg's law. The groundwater, however, pushes the seawater farther offshore side than predicted by the law, giving rise to freshwater flows even below the bottom of the sea. A previous study found that the distribution of submarine groundwater discharge and the point of the seawater/freshwater interface on the marine floor are closely related. The cross-sectional shape of the interface onshore is clarified by using electrical tomography and observation of groundwater and soil samples taken from observation wells located in the coastal area (by a volcanic island and associated deposits). In both fields, diving was carried out to find the submarine groundwater discharge on the sea-floor and to take water samples. From the analysis of the water discharged on the marine floor and/or electric conductivity measurements in the marine sands, it is shown the freshwater flows (discharges) along the interface, even in the submarine deposits. The understanding of groundwater flows at the downstream end of the groundwater flow system (from mountainous to marine) will facilitate the development of water resources and the evaluation of environments.

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INTRODUCTION

Church (1996) reported that the amount of fresh groundwater poured into the ocean through sea-floor discharge is large enough to control the chemistry of seawater in a global scale. While the groundwater is discharged into the ocean as freshwater or in a form close to it, a seawater/freshwater interface always occurs beneath the bottom of submarine slopes where the terrestrial groundwater is discharged. Marui (1997) noted that Syrian people already used the groundwater discharged out of the sea-floor as their drinking water as early as 2000 years ago (similar explanation has been reported from Italy, Greece and Spain). This study also showed the chance of the occurrence of submarine discharge of fresh groundwater globally from the interaction of geology and climate. In the Japanese islands, the annual precipitation ranges from 1600 to 1800 mm in most areas. In general, more than half and about 30% of the total rainfall on land areas is lost through evaporation and superficial discharge, respectively. The rest permeates underground to recharge the groundwater in the drainage basins, though only a small part flows towards the deeper parts of the groundwater reservoir (Kayane, 1980).

To elucidate the pattern of groundwater flow in the coastal area, at the end of the groundwater flow system, research involving electric soundings, the observation of groundwater and diving was carried out on two representative Japanese islands. Studying of the shape of seawater/freshwater interface is an essential port of the elucidation of groundwater flow in the coastal area. It is likely to play an important role in developing groundwater resources and in understanding geological environments at depth.

PREVIOUS WORK

SEAWATER/FRESHWATER INTERFACE AND SUBMARINE GROUNDWATER DISCHARGE

Groundwater springs on the sea-floor, have rarely been an object of study most attention focusing on onshore seawater/freshwater interfaces, particularly as regards the saltwater intrusion in plan view (the salinization of groundwater).

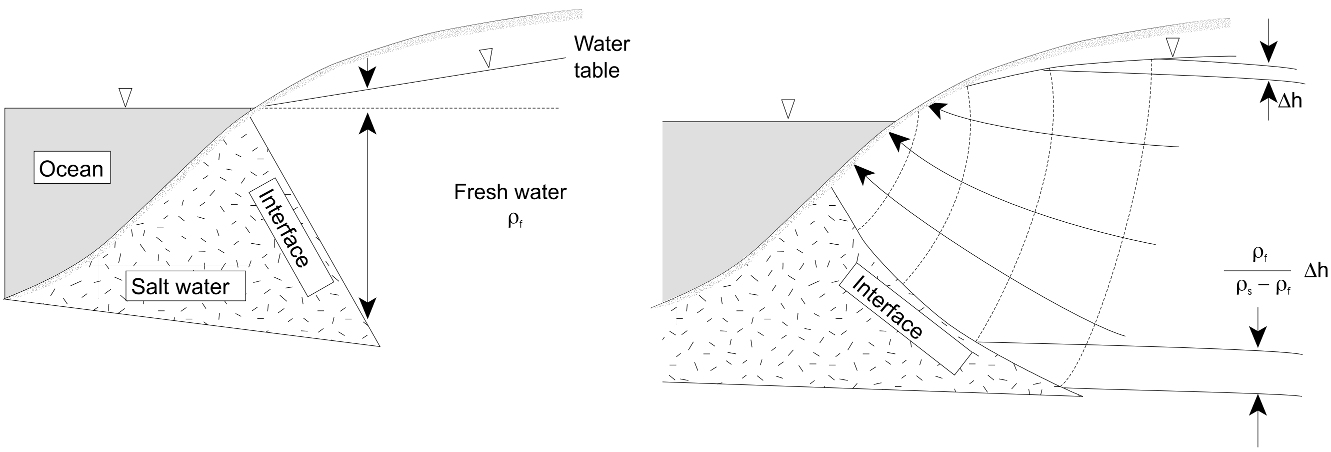

Fig. 1. Shape of freshwater/seawater interface, Gyben-Heltzberg interface (L) and actual interface in the condition of flowing groundwater (R) (after Bower, 1978)

However, groundwater discharged from the sea-floor has recently been regarded as a natural resource, resulting in the initiation of groundwater flow studies including the shape of seawater/freshwater interfaces. Zektzer *et al*. (1973) and Fairbridge (1966) have provided historical reviews of seawater/freshwater interfaces. Notably, Zektzer *et al*. (1973) showed that the amount of groundwater discharge out of the sea-floor is larger than expected, while the submarine groundwater discharge allows estimation of the hydraulic properties of fresh groundwater on the landward side of the discharge. Furthermore, Zektzer *et al*. (1973) estimated the amounts of groundwater discharged into the Caspian Sea and Baltic Sea by reviewing the previous data, and noted that the sea-floor discharge of fresh groundwater amounts to 30 to 50% of the total fluvial outflow on a global scale. They thus surmised that the amount of fresh groundwater discharge is large enough to contribute to seawater quality. Zektzer *et al*. (1973) also reported that the seawater/freshwater interface in the sea-floor discharge of fresh groundwater mostly occurs on the offshore side of the Ghyben-Herzberg interface, indicating that the fresh groundwater is discharged on to the sea-floor and moves upward from depth along the interface (footnote).

Active surveys on the sea-floor discharge of fresh groundwater have been conducted around the Florida Peninsula. Manheim (1967) and Manheim and Paull (1981) drilled into a sea-floor ranging from 200 to 1000 metres deep to collect rock samples and deep groundwater samples, and discovered the discharge of fresh groundwater of continental origin on to the continental slope. Furthermore, work by Schmoker and Halley (1982) and photographs of a 3000 m deep sea-floor by Paull *et al*. (1984) showed that continentally-sourced groundwater travels long distances, and also affects seawater composition. Groundwater discharged on to the deep sea-floor was previously an object of oceanographic study; more recently, it has been studied from the viewpoint of groundwater migration and the seawater/freshwater interface.

NATURE OF THE SEAWATER/FRESHWATER INTERFACE

General forms of the seawater/freshwater interface are represented by Ghyben-Herzberg's law[*]. On the basis of this law, Bouwer (1978) and Freeze and Cherry (1979) argued that the seawater/freshwater interface is affected by the form of water table near the surface and that the surface tip of the interface is pushed away beneath sea level because the groundwater flows under a high hydraulic potential generated in the provenance area (Fig. 1). Thus, the upward migration of groundwater occurs above the seawater/freshwater interface, resulting in the submarine discharge of fresh groundwater.

Groundwater flow is determined by hydraulic gradient and hydraulic conductivity. As long as the interface is approximated by the Ghyben-Herzberg' equation, the true flow rate of groundwater cannot be obtained. In order to obtain an exact flow rate, it is necessary to know the exact distribution of pore pressure in the rock formation, as proposed by Freeze and Cherry (1979). This requires capturing the exact shape of the interface between salt water and freshwater, for example by drilling boreholes normal to the coastline to observe the depth of the interface, as in the study of the shape of seawater/freshwater interface by Kohout (1964). However, this method is rarely feasible due to financial and logistic obstacles. Even if several observation wells are made, pumping of groundwater after the completion of the wells results in moving up onto the onshore side of the seawater/freshwater interface that was below the sea as reported by Reilly and Goodman (1987), or the injection of freshwater as drilling slurry may disturb the interface around the boreholes (Rubin and Pistiner, 1986). Such problems have retarded progress in this field of study.

We have used the following methods to overcome these problems:

1. Taking advantage of several onshore observation wells, resistivity tomography was conducted between individual

[*] Ghyben-Herzberg law: this is a balance equation describing the static equilibrium between fresh groundwater and salt groundwater, meaning that the depth of seawater/freshwater interface below mean sea level is determined by the freshwater head above sea level. However, groundwater usually flows seawards by the effect of a provenance area with a high elevation. The potential pushes out the interface seawards, resulting in submarine discharge of fresh groundwater. Though the law defines the interface as a clear-cut boundary, the boundary in reality forms a transitional zone, which makes it difficult to discriminate the flowing fresh groundwater exactly.

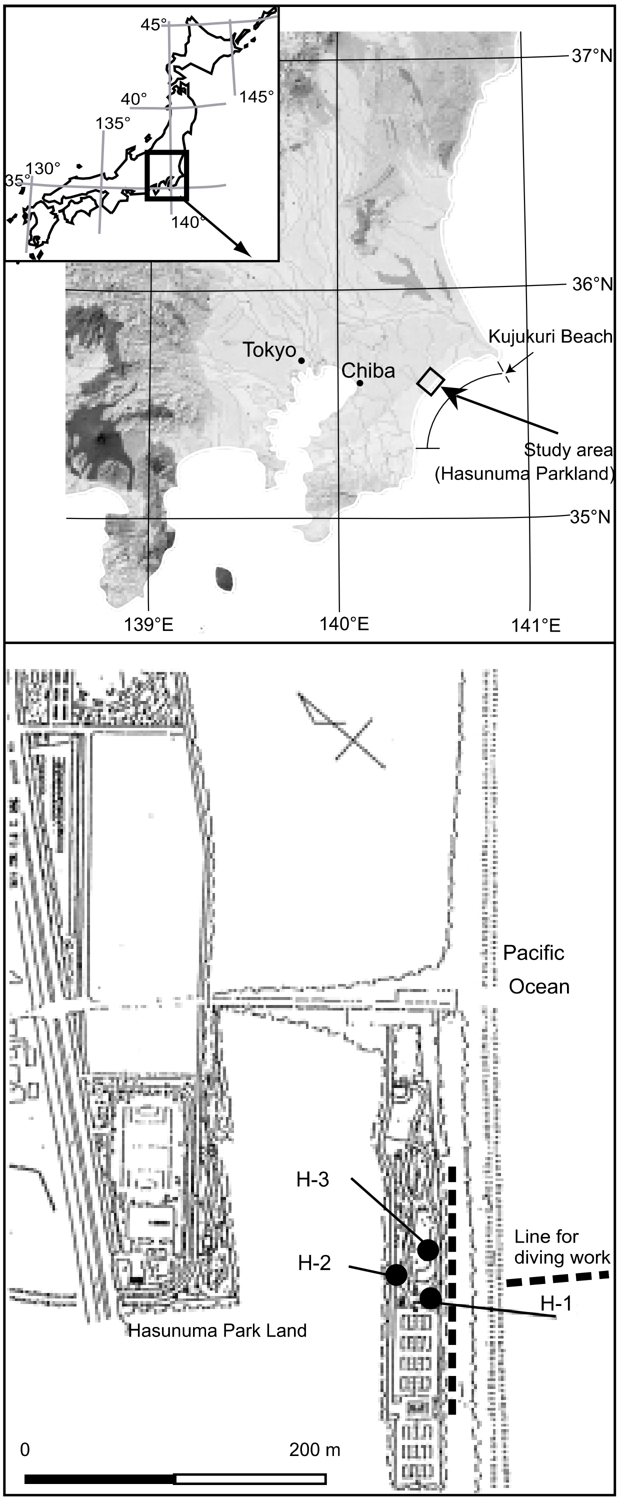

Fig. 2. Map of the study area

wells to measure the depth of the undisturbed seawater/freshwater interface (unaffected by drilling).

2. The onshore observation of the interface and the groundwater discharge on the sea-floor was used to determine, the shape of seawater/freshwater interface as a two-dimensional profile.

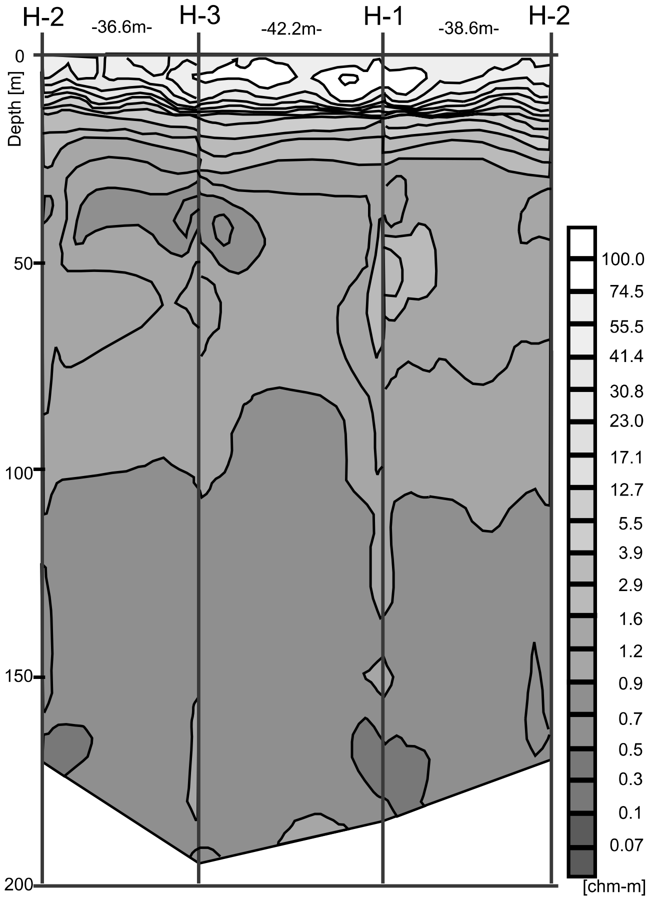

Fig. 3. Results of electric sounding in the non-disturbed area (between wells)

3. Surveys on submarine groundwater discharge at different times enabled a three-dimensional shape of the interface to be obtained.

Quantitative models of the shape of the seawater/freshwater interface resulting from groundwater movement in coastal areas may be abtained by these techniques. These may allow future estimation of the diffusion range of salinity and other factors of the interface.

SHAPE OF SEAWATER/FRESHWATER INTERFACE

RESISTIVITY TOMOGRAPHY BASED ON OBSERVATION WELLS

A study on the shape of the seawater/freshwater interface was carried out in the village of Hasunuma, Chiba Prefecture (the Hasunuma Parkland on the northern Kujukuri Beach). The study area is underlain by horizontal unconsolidated strata, which were expected to carry several bed-shaped seawater wedges (Lusczynski and Swarzenski, 1966). Three observation wells were arranged at apices of an equilateral triangle with *ca* 40 m long sides to measure the depth of the seawater/freshwater interface by well-logging (Fig. 2). The result of resistivity tomography tests carried out between these wells is shown in Figure 3. In the Kokumoto Formation, composed of siltstone, the resistivity decreases downwards, indicating an increase in

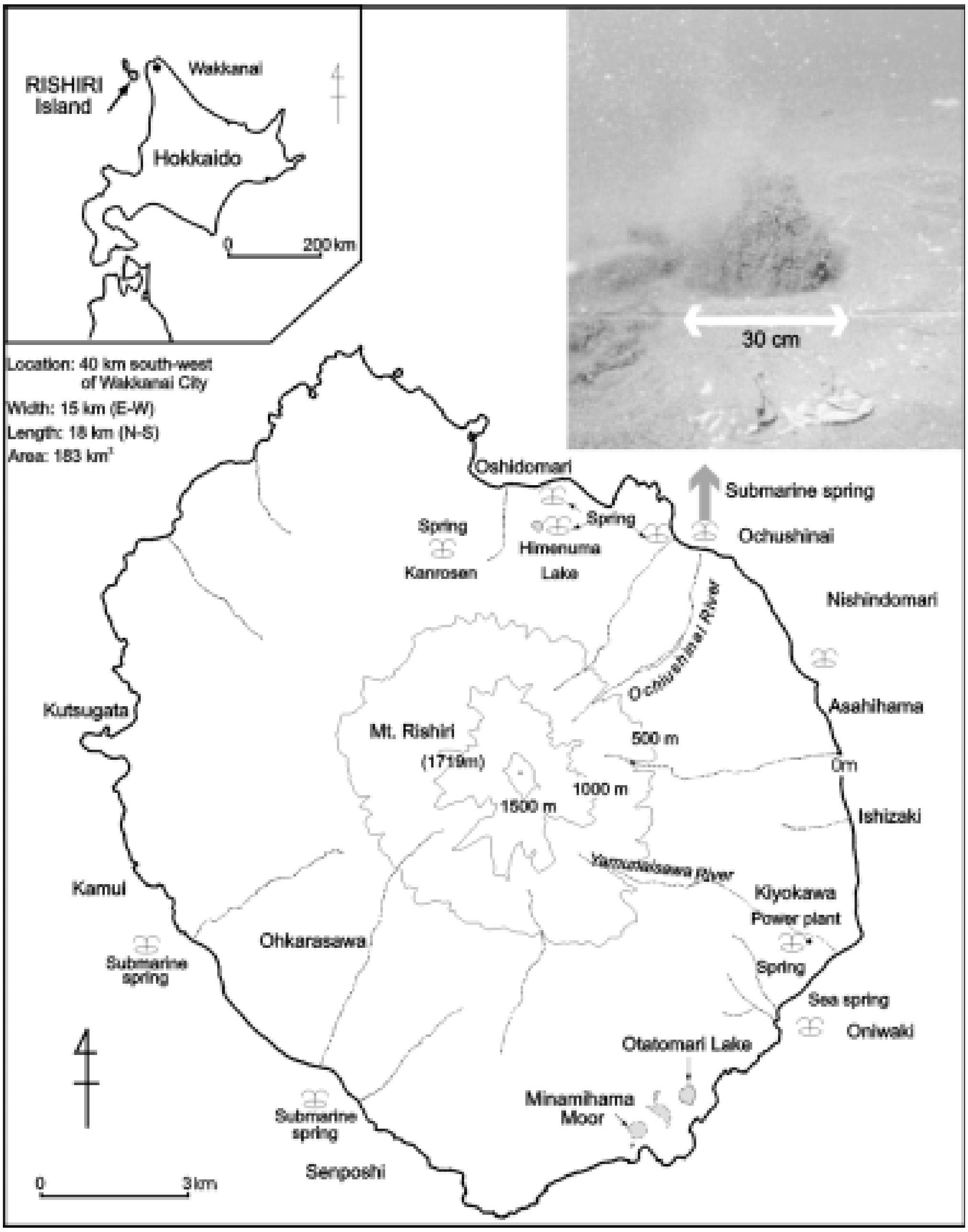

Fig. 4. Submarine groundwater discharge off Rishiri Island

salinity. According to Marui *et al.* (1999*b*), the seawater/freshwater interface is about 175 metres deep at the H-1 borehole. Although tomography tests indicated scant distortion of the interface by the observation wells, the excavation effect was significant in the immediate neighbourhood of the H-1 borehole (it is presumed that at a depth of 110 to 130 metres and about 150 metres in the H-1 borehole and at 155 to 185 metres in the H-2 borehole the salinity is lower in than undisturbed arras). Thus data from observation wells only is not enough to measure the exact depth of the seawater/freshwater interface. A schematic profile of the H-1 borehole in Figure 6, shows that there are two aquifers at a depth of less than 200 metres in this area, each of which has a seawater/freshwater interface (corresponding to the observation by Kiyama and Marui, 1999). The depth of the interface (some 175 metres) not only proved to be quite different from the value estimated by the Ghyben-Herzberg's law (estimated at about 60 metres on the basis of the water table; 1.5 m a.s.l.). It has also became evident that salt water has invaded dune sediments to form thin layers and that fresh groundwater has pushed out the interface on the offshore side became of the high potential provided by the sources mountains. One can thus expect fresh groundwater discharges on the sea-floor.

DIVING SURVEYS OF THE SUBMARINE SPRING AND OF SEA-FLOOR FRESHWATER SEEPAGE

Marui *et al.* (1999*c*) conducted a survey of the groundwater discharged on the sea-floor in the Rishiri Island, Hokkaido. The

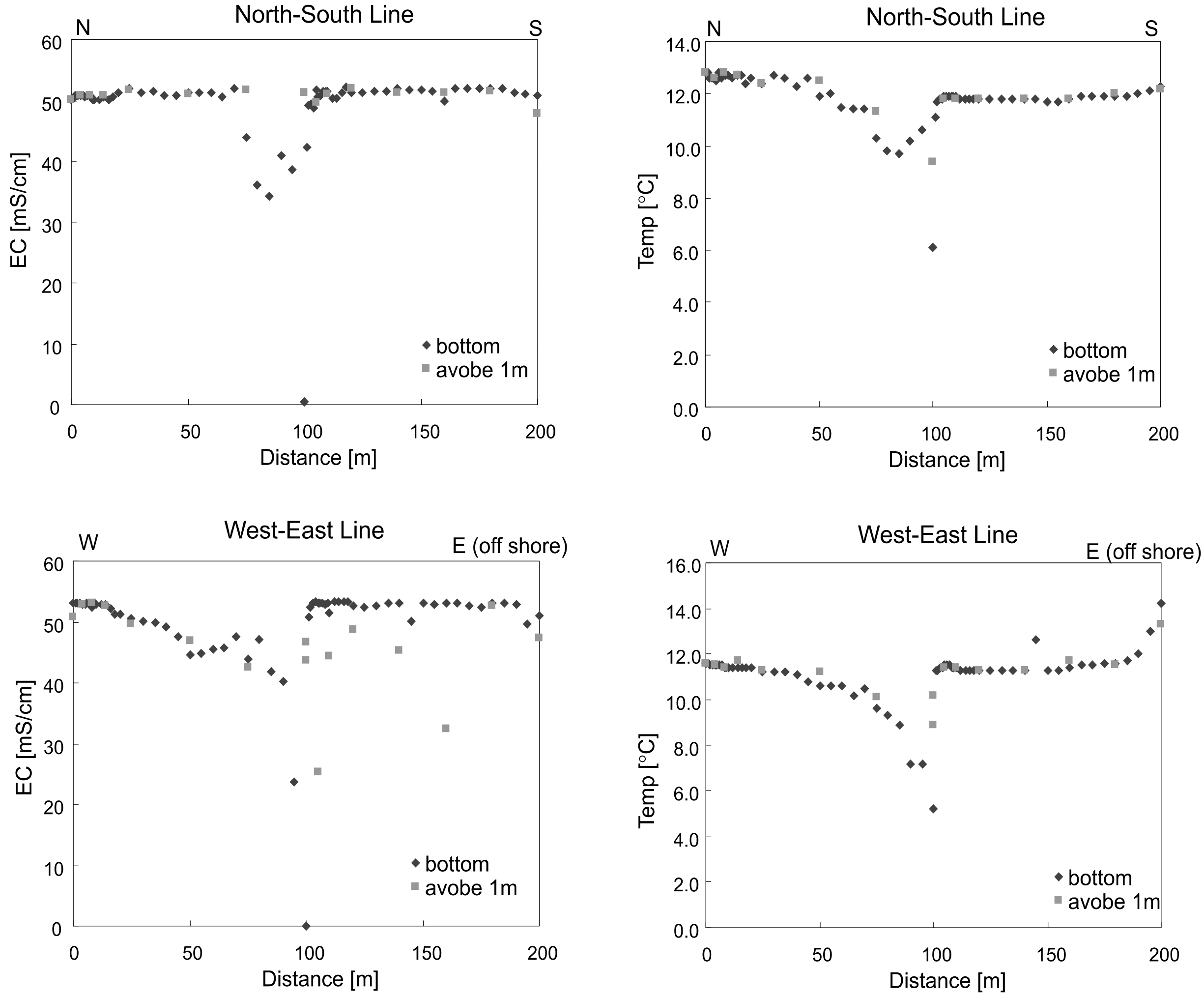

Fig. 5. Results of diving studies about electric conductivity (EC) and temperature around the interface off Rishiri Island

groundwater discharge was identified at several points off the Ochushinai district of Rishiri Island as shown in Figure 4. It is assumed that the groundwater discharged on the sea-floor is of land-origin and forms a seawater/freshwater interface before discharging (caused by the freshwater flow under the marine floor). Effects of the fresh groundwater discharged in the seepage area (along the interface) are seen in sand deposits around the submarine springs as shown in Figure 5. Measurements of electric conductivity indicate some turbulentce (the effects of an ocean current) on an east-west section. However, temperature measurements show the effect of the discharge of fresh groundwater on the north-west side (land word side), implying that the seawater/freshwater interface is on the immediate offshore side (south-east side) of the submarine springs. Thus, this survey showed that temperature measurements were useful for identifying the submarine discharge points of fresh groundwater.

Marui *et al*. (1999*a*) also conducted a diving survey to verify the discharge points of fresh groundwater off the Kujukuri Beach. The outline of the survey is shown in Figure 6. Based on the results of the survey, the form of the seawater/freshwater interface was reconstructed as shown in Figure 7. For convenience of computation, a cross-section perpendicular to the shoreline is considered. While the origin of the coordinate axes is put at the beach, the X axis is placed along sea level and the vertical line passing the origin is selected as the Y axis. According to Marui *et al*. (1999*a*), the observation well is underlain by a loosely consolidated sand layer containing an aquifer from the surface to a depth of about 26 m. At the landward side of the beach, the water table always ranges between 0.7 and 1.5 m a.s.l. (the land surface level is 2.2 m a.s.l.). The well is underlain by siltstone of the Kokumoto Formation from a depth of 26 metres to the well bottom exceeding 200 metres deep. This formation is also an aquifer. According to Freeze and Cherry (1979), the moving fresh groundwater pushes out the salt water to develop a submarine discharge. Accordingly, it would be realistic to suppose that the freshwater potential is balanced with the seawater density as shown in Figure 7. Assuming that the seawater density is 1.025 g/cm^3 (ρ_s) and the freshwater density is 1.000 g/cm^3 (ρ_f), the gradient of the depth of the seawater/freshwater interface can be calculated as follows:

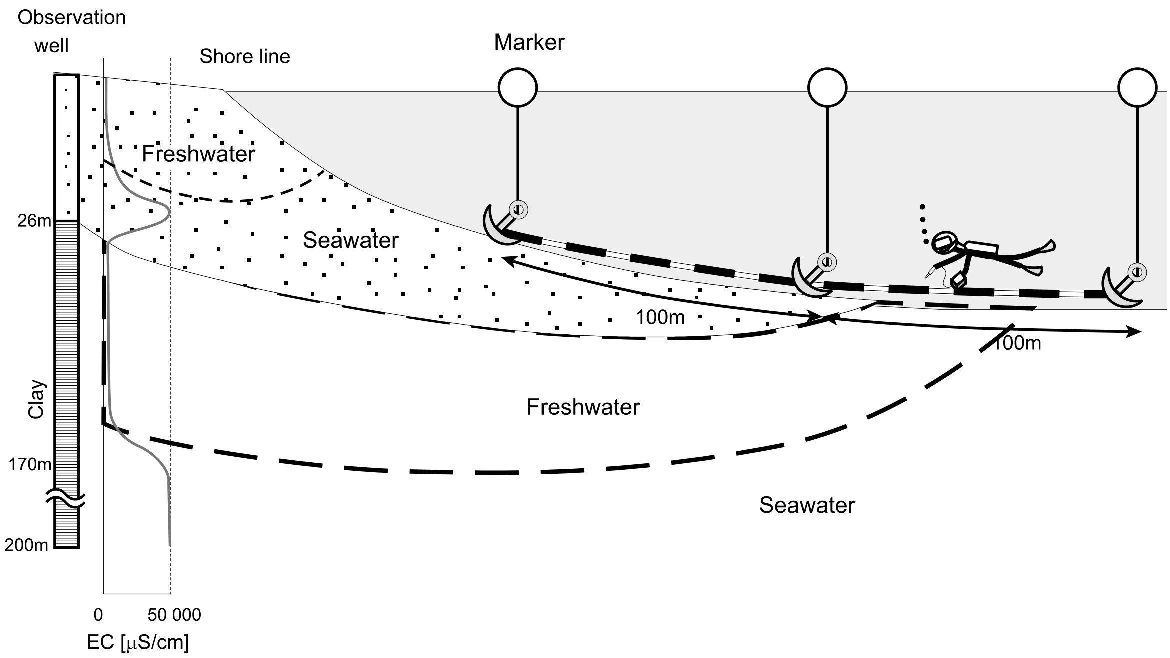

Fig. 6. Outline of diving research for electric conductivity (EC) and temperature

$$\frac{dH}{dX} = \frac{\rho_f}{\rho_s - \rho_f} \cdot \frac{h}{l} = 0.3 \qquad [1]$$

where: the distance between the beach and the observation well (l) is 200 metres and the water table elevation in the well (h) is 1.5 metres a.s.l.

Taking into account that the difference between the water table elevation and the depth of the seawater/freshwater interface is virtually equal to the pressure head, the submarine groundwater discharge occurs at a distance from the shore line (L = 320 m) and a depth of H_1 = 4 m (Marui *et al*., 1999*c*), and the seawater/freshwater interface in the observation well is 175 metres (H_2) below the sea level, the gradient of water table being:

$$\frac{dh}{dX} = \frac{h}{l} = \frac{1.5}{200} = 0.0075 \qquad [2]$$

and the gradient of seawater/freshwater interface being:

$$\frac{dH}{dX} = \frac{H_2 - H_1}{l + L} = \frac{171}{520} = 0.32 \qquad [3]$$

Thus the following relationship is obtained from the above two formulae;

$$\frac{dh}{dX} = 42.67 \frac{dH}{dX} \qquad [4]$$

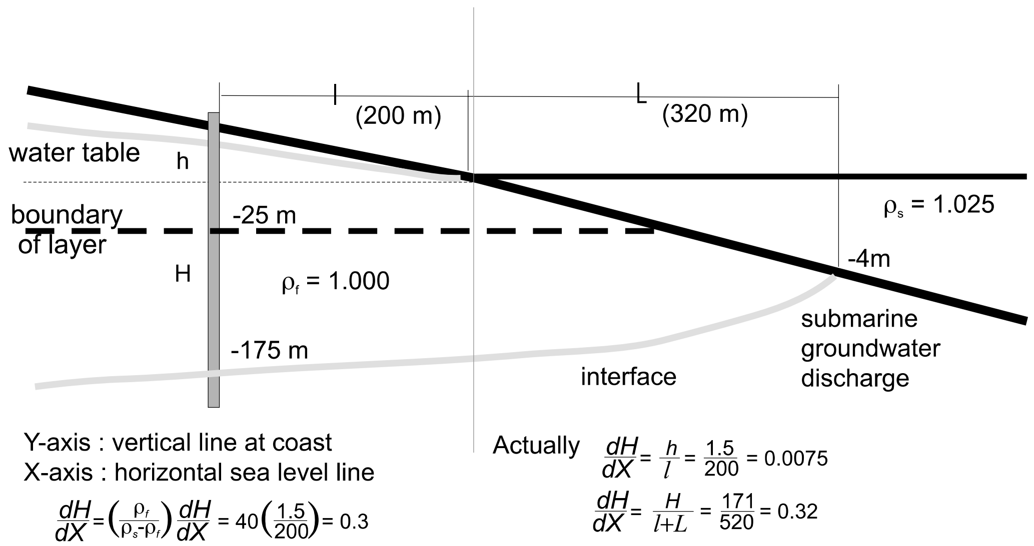

Fig. 7. The shape of the freshwater/seawater interface

The ratio between the gradient of the water table and the gradient of the depth of the seawater/freshwater interface is approximately equal to the ratio ($\rho_f/(\rho_s-\rho_f)$). The linear approximation of the shape of seawater/freshwater interface is expressed as follows:

$$Y = \frac{dH}{dX}\cdot X - \left(\frac{dH}{dX}\cdot l - 175\right) \quad [5]$$

As the groundwater discharged on the sea-floor actually has a vertically-upward flow component, the differential value at the discharge point needs to be normally-upward. Taking this and the discharged point location (4 m depth and 320 m offshore) into consideration, the shape of seawater/freshwater interface is reasonably approximated by a quadratic equation as follows:

$$\frac{dH}{dX} = \frac{d}{dX}\left(-\sqrt{X-4}+320\right) \quad [6]$$

Supposing that the pressure distribution in the aquifer is represented by this equation, the flow rate of groundwater moving in the Kokumoto Formation across the beach is estimated at 0.42 m^3/unit width/day taking the aquifer of fresh groundwater to be 151 metres thick, the hydraulic gradient to be 0.32 and the hydraulic conductivity to be 1×10^{-7} m/s (*c.f.* 0.0098 m^3/unit width/day by using the normal hydraulic gradient of the groundwater surface which is 0.0075 in Figure 7). Assuming that these values, such as hydraulic gradient and hydraulic conductivity, are applicable to all the aquifers in the survey area, the quantity of groundwater flowing across the 4000 m long beach totals up to 1680 m^3/day (when the hydraulic gradient is 0.32).

CHANGE IN THE GROUNDWATER DISCHARGE AREAS AND CHANGE IN THE 3-D SHAPE OF SEAWATER/FRESHWATER INTERFACE

The results of diving surveys of the submarine discharge of groundwater are shown in Figure 8, which summarises the results of three diving surveys conducted in 1999 and 2000. As shown in Marui *et al*. (1999*a*), the individual surveys consist of measurements of electric conductivity and water temperature in sand deposits on the sea-floor to identify the fresh groundwater discharge along the traverse lines. Probable discharge areas detected along the individual lines traversed in different seasons are hatched in Figure 8. Three discharge areas were expected in this area. In zone A of Figure 8, the distance between the beach and the discharge point considerably differs from one line to the other. This might be due to either migration of the discharge point or the irregularity of traverse lines according to seasons. While zone B is characterised by a nearly identical discharge point, the discharge was observed only once in zone C. These facts indicate that the discharges in zone A and zones B and C originated in the uppermost salt water wedge and the lower clay bed respectively.

Since the groundwater level (potential) of the uppermost aquifer is strongly affected by precipitation during the rainy season or typhoon, the shape of salt water wedges as well as the location of submarine discharges should be changeable. However, the shape of the seawater/freshwater interface related to deep aquifers does not seem to undergo a large seasonal change. In addition, even observations with in a small area with a width of 150 m showed a partial distribution of fresh groundwater discharge. According to Marui *et al*. (1999*b*), the present area forming part of the Kujukuri Beach is expected to be underlain by horizontal strata, so that the partial distribution of groundwater discharge could be also generated by factors such as ocean currents.

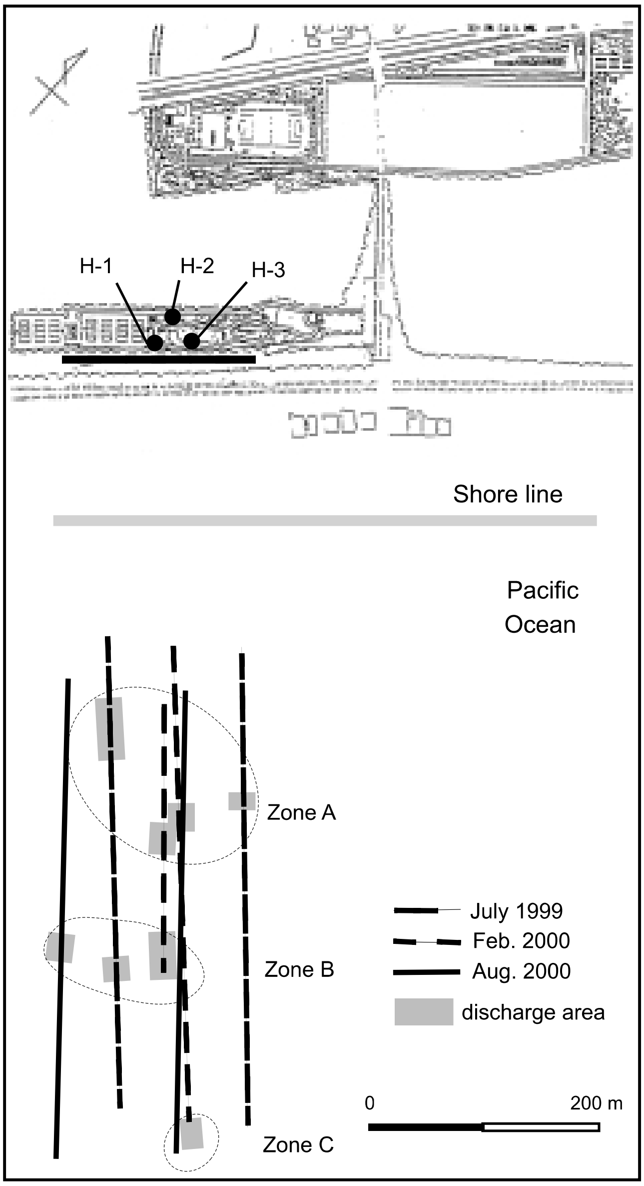

Fig. 8. Results of diving research through 1999 to 2000

The shape of the seawater/freshwater interface proved to be three-dimensionally uneven enough to result in localised groundwater discharges. Although a sedimentary basin with a simple geological structure might be expected to have a simple distribution of groundwater discharge, the irregularity of the submarine discharges (seepages) may be likened to the distribution of springs on land. In this respect, submarine discharge zones extending for tens of metres hardly occur in on shore areas, implying that the submarine groundwater flow (and the seawater/freshwater interface) is simpler than that in the shore zone.

CONCLUDING REMARKS

By reviewing previous studies of the seawater/freshwater interface and of submarine groundwater discharge, the following conclusions may be reached:

1. For a quantitative discussion of the shape of seawater/freshwater interfaces, it is important to ascertain their exact shapes by applying the tomography technique to observation wells devoid of excavation disturbances which would lead to an overestimation of the interface depth. An important future task is to measure the diffusion range of salinity;

2. While the present studies of submarine groundwater discharge and of the seawater/freshwater interface indicate that the shape of the interface can be nearly approximated by a line, it proved to be desirable to adopt a quadratic equation to exactly express the submarine discharge site;

3. The distribution of submarine groundwater discharges indicates that the shape of seawater/freshwater interface is horizontally variable.

By not only expanding the observation area but simultaneously surveying the geology and ocean currents in the future, factors affecting the shape of the seawater/freshwater interface may be explored.

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